A Study of Internal Waves and Turbulence above Irregular, Sloping Bathymetry: A Contribution to the Littoral Internal Wave Initiative (LIWI)

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LONG-TERM GOALS

The long-range goal of our studies is to understand the processes that cause mixing in the ocean. Of particular interest is the turbulence caused by internal wave breaking. Our recent work has revealed strong relationships between finescale shear levels and the intensity of turbulent mixing, and marked spatial variability in the intensity characteristics of the internal wave field. In particular, we have found enhanced finestructure and microstructure adjacent to rough bathymetric structures. We seek to develop sufficient understanding of internal waves near such bathymetry as to produce models that can predict the magnitude and variability of turbulent mixing resulting from internal wave breaking.

OBJECTIVES

A field program was conducted in May of 1998 to quantify finescale internal wave characteristics above a region of irregular, sloping bathymetry. Analysis of the data will focus upon two basic mechanisms for modifying the internal wave field in the littoral zone: internal wave generation at, and wave reflection from, the bottom. Both can result in enhanced internal wave shear and strain, and in turn, increased occurrence of shear and/or advective instability supporting turbulence and mixing.

Our objectives in this current grant are two fold. First, we will relate the field measurements to the generation/reflection processes which may produce enhanced finescale internal waves. Specifically, we will be testing and refining models of wave generation/reflection. Secondly, we will develop and test dynamical models which predict the spatial and temporal evolution of an enhanced finescale internal wavefield as it propagates away from the bottom boundary. Such dynamical models will

result in a prediction of the rate internal wave energy dissipates and results in turbulent mixing.

APPROACH

The field program utilized a combination of vertically profiling instrumentation. The first instrument was the free falling High Resolution Profiler (Schmitt *et al*., 1988) which obtains samples of the ocean's temperature, salinity, and horizontal velocity field and dissipation rates of turbulent kinetic energy and temperature variance. The second instrument was a moored profiling instrument (the Moored Velocity Profiler, MVP) which is able to sample oceanic velocity, temperature and salinity variability. Third, employed a Lowered Acoustic Doppler Current Profiler/Conductivity Temperature Depth (LADCP/CTD) system. Finally, Eric Kunze from the University of Washington deployed expendable instrumentation [eXpendable Current Profilers (XCPs) and eXpendable CTDs (XCTDs)].

The experimental site is characterized by well defined, small horizontal scale (2.5–3 km horizontal wavelength) ridges oriented onshore-offshore and superimposed on a large-scale planar slope, Figure 1. Three MVP's were deployed as a coherent array with an approximate spacing of 500 m. The array was located in about 1150 m water depth on the continental slope just north of Cape Hatterras (36 34'N, 74 39'W). The HRP was used to repeatedly sample a grid of stations in water depths of 800-1800 m about the MVP array. The LADCP/CTD was typically deployed in water depths shallower than 800 m. Expendable operations were concentrated on a site 10 km to the north of the moored array. In combination, these vertical profile data will allow us to characterize the amplitude and direction of propagation of the finescale internal wavefield. This information will permit an assessment of the various generation/reflection processes.

Our research effort benefits from the technical support of several people here at WHOI. Ellyn Montgomery maintains the HRP sensors and control processor and its associated data acquisition and reduction systems. The instruments mechanical systems are maintained by David Wellwood. Maggie Cook and Gwyneth Packard assist the PI's with reduction and analysis of the acquired data. The MVP technical activities are being supported by folks in the Institution's Advanced Engineering Laboratory.

WORK COMPLETED

Cruise preparations were completed. This included: the construction of two MVPs and reburbishment of a third, development of software for the analysis of MVP data, and analysis of existing ancillary data (i.e. historical current meter and CTD data) to refine the sampling strategy. Cruise preparations were complicated by an explosion within the HRP pressure case, which apparently was triggered by a faulty battery. That the cruise happened on schedule is due to the dedication and experience of many people associated with WHOI. Ellyn Montgomery directed the repair efforts. Significant engineering support and assistance in testing were contributed by Marshall Swartz, Steve Liberatore, Dick Koehler and Al Fougere. Assembly assistance and spare parts were obtained from Karlen Wannop, Jim Valdes's group and Craig Taylor.

The cruise did not get off to a smooth start. Immediately following arrival on site, the HRP was lost and one day was spent attempting to reacquire the HRP. Activities in the following two days were limited by weather. An additional four days were spent deploying, checking the functionality of,
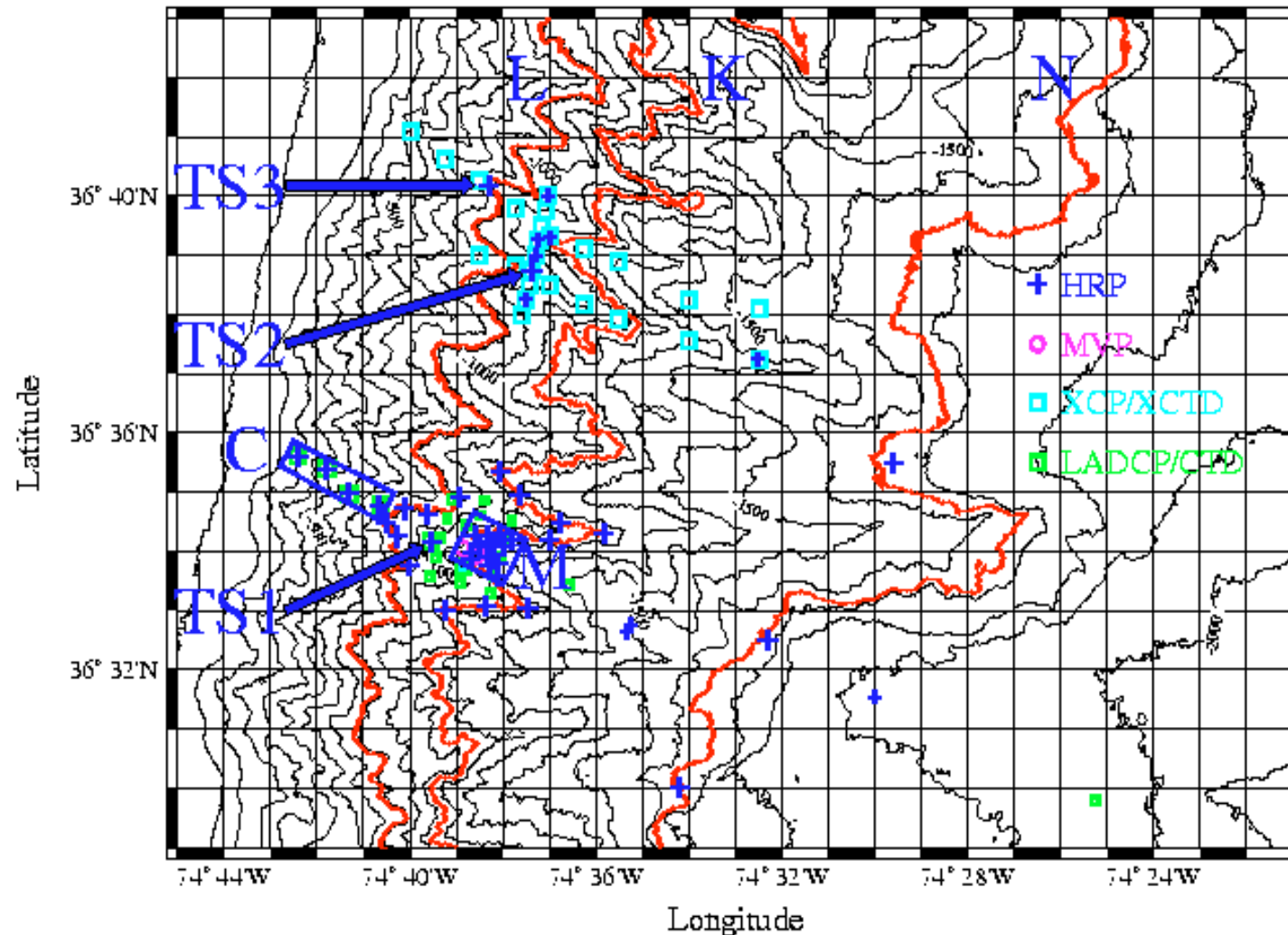
TWIST

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Figure 1: Sampling plan for the TWIST (Turbulence & Waves over Irregularly Sloping Topography) field program. Bathymetry is contoured in intervals of 100 m. The symbol and color key for the various instruments appears within the plots. Large symbols denote reoccupied stations. The red bathymetric contours denote water depths of 880, 1150 and 1670 m. The HRP work was confined to these bathymetric contours for most of the field program. The "L", "K" and "N" notation signifies grids of reoccupied stations on the 880, 1150 and 1670 m isobaths, respectively. The "M" notation denotes a repeated grid about the MVP array, and "C" denotes an across shelf grid in water shallower than 800m. Time series are depicted with the notation "TS".

repairing and redeploying two of the current meters. These four days included the reacquisition, loss and second recovery of the HRP. Despite the initial difficulties, we came back with the high quality data we intended to acquire. Roughly 90% of the intended grid sampling was accomplished with either the LADCP/CTD or the HRP. In total, 214 HRP, 48 LADCP/CTD and 108 XCP/XCTD profiles were obtained. Approximately 815 velocity and CTD profiles were obtained from the MVPs.

RESULTS

We are still at the stage of processing data from the field program. Preliminary analysis of the data, however, reveals that turbulent mixing was greatly enhanced above rough bathymetry on the Continental Slope, Figure 2. Vertical profiles of turbulent diffusive ($K_\rho = 0.25 \, \varepsilon/N^2$) uniformly indicate a bottom enhancement. At the moored array, the turbulent diffusivity in the bottom 200 m is approximately $20 \times 10^{-4} \, m^2 s^{-1}$, more than two orders of magnitude larger than that estimated in the upper 100 m of the water column. Further offshore, the turbulent diffusivity decreases. Within the Gulf Stream (not shown), vertical mixing is weak ($O \sim 10^{-5} \, m^2 \, s^{-1}$) and independent of depth. The data indicate a maximum in turbulent mixing during the middle portion of the field program. This temporal variability in the turbulent mixing can be linked to distinct, high wavenumber features in the MVP velocity records. Our current hypothesis is that these features represent a quasi-stationary internal lee wave response to along slope flow over the rough bathymetry.

IMPACTS/APPLICATIONS

As part of this grant, a novel dynamical model was developed which permits the assessment of wave propagation and non-linear interactions in determining the energy balance of the finescale internal wavefield. While the model is highly idealized in it's present form, we expect that appropriate modifications can be made to provide robust estimates of the spatial and temporal evolution of the internal wavefield and turbulent dissipation in continental slope regions. The field program described above will help ground truth the model.

TRANSITIONS

A manuscript describing the dynamical model results outlined above is in preparation. The results have been presented in seminars at the University of Washington, University of Victoria, Woods Hole Oceanographic Institution, and Bedford Institute of Oceanography. We have invited Steve Thorpe (Univ. of Southampton) to the United States to explore collaborative projects. Dr. Thorpe obtained ONR funding to do so. Sonya Legg (WHOI) has obtained ONR funding for numerical studies of internal wave processes in the littoral zone. We anticipate working closely with Dr. Legg.

RELATED PROJECTS

We used three Moored Velocity Profilers in the field experiment. Alterations to the pre-exisiting Moored Profiler, which carried only a CTD, were funded by ONR (grant to J. Toole and R. Schmitt). As well, refurbishing of the prototype MVP and construction of two new MVP's was funded under a companion DURIP grant (J. Toole & D. Frye). Eric Kunze (UW, XCP and XCTD deployment) participated in the field program. Finally, the insight gained as part of this grant will have a direct impact on the interpretation of HRP and tracer data acquired during the Brazil Basin Experiment (NSF grants to J. Ledwell, J. Toole and R. Schmitt).
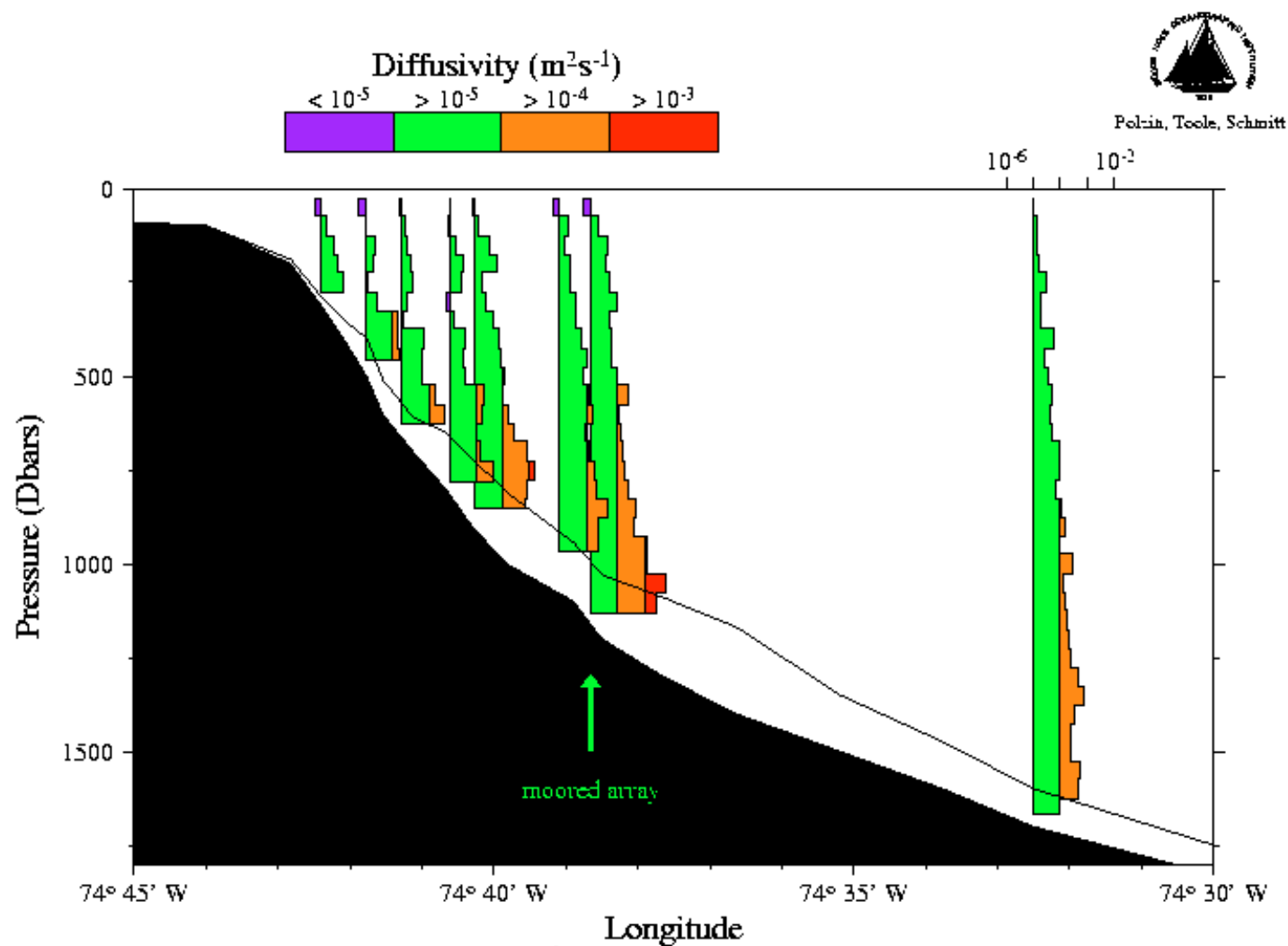
Figure 2: Averaged profiles of vertical diffusivity ($0.25 <\varepsilon>/<N^2>$) from the reoccupied grids. The diffusivity estimates are plotted on a logarithmic axis with a decadal color scheme. From left to right, the profiles represent the 'C' grid (the first four profiles), the 'L' grid, 'TS1', 'K' and 'N'. Dark shading represents topography within a valley. The solid black line represents the height of adjacent topographic ridges. Individual profiles in the 'L', 'K' and 'N' grids were obtained along isobaths, so that the position of the corresponding average vertical diffusivity profile in longitude corresponds to the western most profile of that grid. The longitude of the eastern most station of a grid can be ascertained by drawing a horizontal line eastward, from the bottom of the vertical profile to beyond the intersection with the solid black line.

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PATENTS

U.S. patent awarded August 1998 for the WHOI Moored Profiler, Co-Inventors K. Doherty, D. Frye and J. Toole